SIMULATION OF SHAPE, LIGHT, COLOR AND MATERIAL IN DESIGN

Luca Caneparo

School of Architecture
Polytechnic of Torino - Torino, Italy

Abstract

The purpose of this paper is to analyze the role of simulation in architectural design. The concept of simulation is taken over from physics, where analytical relationships are set up between measured phenomena and mathematical models. Computer visualization applies quantitative models to physical phenomena to simulate analytical aspects, and offers to the designer programs to evaluate, in C.A.D. models, the visual qualities and the numerical quantities of the interactions between shape, light, color and material.
Regarding the light-matter simulation, the paper presents an overview of the evolution in the mathematical models used in both commercial and research software.
Regarding the visualization of materials, the paper presents recent developments in geometry which make it possible to visualize not only the surface appearance but also the in depth structure of building materials.

Introduction

Isaac Newton’s *Optical Lectures* (1728) may be symbolically regarded as the turning point in studies of light, color and perception. Newtonian theories replace geometric optics which had been a recurrent, though not constant, concept from Euclid to Descartes.
The experimental results of geometric optics form the basis for the *perspectiva artificialis*, a strictly geometric method of determining, on a two-dimensional plane, the proportions of any object inside the visual pyramid of the subject.
The experimentation on perspective method, carried out by Brunelleschi himself, the famous "tavolette" showing the view from the Baptistery of San Giovanni (Manetti 1976), were used by the designer of Santa Maria del Fiore to investigate the bases of the geometric method which sets up a relation between two-dimensional representation and the corresponding perceived reality.
The importance of these experiments lies in the biunivocal correspondence which they set up between empirical reality and geometric laws. This correspondence allowed Renaissance architects to make the *perspectiva artificialis* a working tool for use in the study of concrete cases. For Renaissance architects the perspective method becomes a working tool for the study of the collocation of the subject in the architectural space, and for the analysis and presentation of the effect and

building hypotheses of the designs. Together with perspective, light and shade are used to analyze and show lighting problems, which are another important application of geometric optics, frequently used in architectural design. The judicious use of light, and of the alteration of areas of light and shade, contribute to the creation of a powerful illusion in perspective designs, as can be seen in Bramante's design for S. Maria del Popolo and in the Prevedari engraving (Bruschi 1969), or, later, in baroque architecture.

Newton's laws represent the transition from the geometric- qualitative plane, directed towards subject and perception, to the algebraic-quantitative plane, directed towards object and objectivation of the real, by means of the analytical organization of phenomena and their quantitative analysis. Establishing that energy is the link through the illuminating and illuminated objects justifies the techniques of measurement and graduation of emission intensities and at the same time justifies the transfer of knowledge on to the plane of quantitative dimensions. The success of the exact sciences derives from the transfer of cognitive experience on to the plane of algebra, which sets up an exact quantitative correspondence between hypothesis and experimental confirmation. This has permitted the discovery that the physical world corresponds with mathematical laws.

In Newton's *Optics*, the theory of the angle of incidence, refraction, reflection, sets up an objectifying principle for solving deterministically both the problem of light, illumination, color, and that of perception.

In opposition to the Newtonian laws, Goethe supports a physiological dimension of perception. Goethe's theory implies the overturning of the point of view, concentrating attention on the subject and on the peculiarity of perceptive processes. In an artistic and philosophical context, Goethe's theories are supported by the change in role attributed to the subject and the denial of experimentalism. Although many of Goethe's theories have been disproved scientifically, thus invalidating his conclusions, the basis of his hypotheses seems to be correct: he denies the supposed determinism of physics, specifically as regards the objectification of relationships between electromagnetic magnitude and psychological-perceptive processes, which have proved impervious to determinism.

Light and Color

In order to simulate the interactions between shape, light and color, computer graphics (C.G.) acquires mathematical models from physics. In the last thirty years, different models have been tested with a view to simulating more exactly the propagation of light from the source towards the observer. As computing costs have fallen, the algorithms have dealt with increasingly general and complex physical phenomena, including progressively the effects of reflection, transmission, absorption of light.

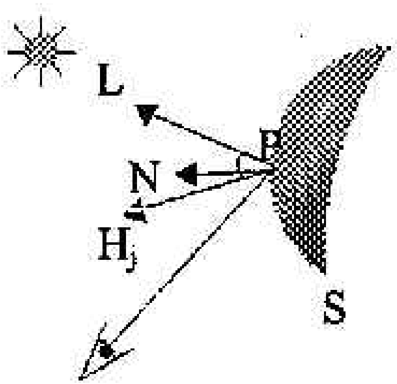
The early simulation models dealt exclusively with direct illumination. Later, in the eighties, models were used which also simulate indirect illumination and diffuse and specular inter- reflection. Each algorithm is still of great importance and can be found, with various implementations, in difFerent programs. In chronological order, these algorithms are:

Gourand (1972), consider the lights as point sources; the intensity of light received form a point on the surface of the object is subdivided in the contributions respectively of ambient, diffused and reflected light (1).

$$(1) \qquad I = I_a + k_d \sum_j \overline{NL_j} + k_s \sum_j \overline{NH_j}$$

where:

- I is the reflected intensity,
- I_a is the reflection intensity due to ambient light,
- k_d is the diffuse reflection constant,
- k_s is the specular reflection coefficient,
- $\underline{N}$ is the unit surface normal in P,
- L_j, is the vector in the direction of the jth light source,
- H_j is the vector in the direction halfway between the viewer and the jth light source.

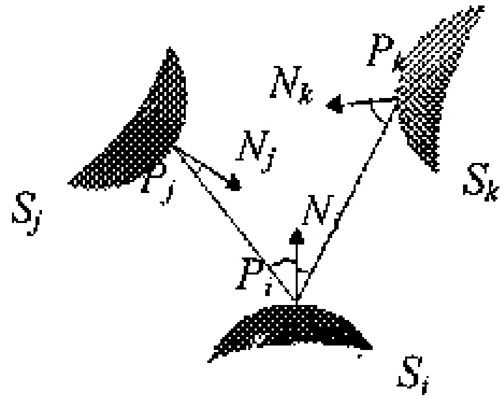


The diffused light varies according the cosine of the angle between the direction of the light source and the vector perpendicular to the surface (Lambert's law). The reflected light varies according the cosine of the angle between the axis of observation and that of reflection. Gourand resolves the equation in accordance with the vertices of polygons, calculating the normal at the points as an average of the normals of the surfaces which are encountered there; this devices allows a notable computational saving, in that the values are calculated only in the relation to vertices, while the intermediate points on the rest of the polygon are determined by interpolation between those of the vertices.
Phong (1975), the interpolation between the values calculated at the vertices, propose by Gourand, tends to make uniform, or indeed to reduce, the areas of specular reflection. The solution might solve the equation in relation to each point on the surface. To reduce the considerable computational cost of the solution Phong proposes to interpolates the normal along the polygon, rather then the values of luminosity. The specular component of the illumination is calculated for every point, rather only in relation to vertices. This produces a better representation of the reflections, although at the price of an increased computational cost.
Ray tracing (Whitted 1980), to gain the effect of reflection and transparence which certain materials produce (e.g. glass and polished metals) it is necessary to trace back the route followed by each single ray of light. The algorithm follows the opposite direction to the propagation of light: starting from the point of view, each individual ray of light which passes through each pixel on the plane of the image is traced back. The route of each ray is traced from the point of view across the projection plane to the object, and, if the surface material is reflecting or translucent, the tracing goes back to another object, and so on until the ray is originated from the light source.

$$(2) \qquad L_{ij} = L_{ij}^{E} + \sum_{k} \int_{S_k} R_{kij} L_{ki} A_{ki} G_{ki} \, dS_k$$

where:

- L_{ij} is the reflected radiance leaving surface S_i at point P_i in the direction of point P_j,
- L^E_{ij} is the the emitted radiance from point P_i in the direction of point P_j,
- R_{kij} is the bidirectional reflectance of surface S_j between directions $\overline{P_k P_i}$ and $\overline{P_i P_j}$,



- L_{ki} is radiance leaving surface S_k at point P_k in the direction of point P_i,
- A_{ki} represents the medium, if P_i and P_k are not mutually visible then $A_{ki}=0$,
- G_{ki} is a geometrical factor depending on distance and orientation of P_i and P_k..

Radiosity (Goral et al. 1984), thermodynamics offers the physical background to this algorithm: every surface is considered as part of a Lambertian body, which reflects light with equal intensity in all directions. The algorithm subdivides each polygon into ever smaller unitary elements and computes for each of them the sum of the energies emitted by all the others. The resulting equation system (3) represents the interchange of energy of the environment, both reflected and emitted.
The equation (2) can be semplified in (3) because the environment is considered perfectly diffuse, that is surfaces have no angular dependence on the bidirectional reflectance function R.

$$(3) \quad L_i = L_i^E + R_i \sum_k L_k \int_{S_k} A_{ki} G_{ki} dS_k \,,$$

where:

- L_{ij} does no longer depend on j and L_{ki} on i (radiosity is constant, whatever the direction),
- R_{kij} does no longer depend on k and j (bidirectional reflectance is constant).

Solving the system (3) offers a discrete representation of the diffuse shading of the scene. Light emission is independent of the point of view, hence this algorithm, once the values of the equations of a scene have been computed, allows rapid generation of new points of view and so can be implemented in simulation programs and is promising for application in virtual reality.

Chiaroscuro

Each algorithm has its own peculiar style in rendering the image, so that we can even speak of schools, like the schools of painting. For the designer, the use of a program which uses one algorithm rather than another implies substantially different presentations of design form. For example, Gourand visualizes shapes with clearly defined edges in which each face is distinguished by a different shading, according to the different incidence of illumination (figure 1, central part), while shadows help to increase perception of the form. With Phong, the shapes are continuously shaded (figure 1, right- hand part), while the highlight on the surfaces brings out the details.

The different algorithms are differentiated by a growing complexity and sophistication of the physical models employed. The aim of this increasing complexity is the "exact" representation of the physical world, even at the cost of increased computational complexity. The goal is meticulously realistic rendering of the detail: each single element of the image has such formal perfection that the whole -the compound sum of the single elements- recalls hyper-realistic painting. In this sense, the influence of science and technology extends into the field of representation, beyond printing and photography, in the direction of an objectivation centered on the relationship matter-color-energy-light. In C.G. pictorial hyper-realism becomes photo-realism, which means aiming at a rigorous representation which, insofar as it applies models from physics, can be identified with the photograph of a real object.

The images obtained with ray tracing and radiosity algorithms are both "exact" from the point of view of physics, however recognizable for the specific nature of the representation, so that a designer would prefer one to the other according to the context in which it is applied.

Ray tracing deals with great precision the reflection and transparence of materials. The light is bright and although its intensity decreases with the distance from the source, the light and dark effects produced by the shadows are clear and the edges sharp. This algorithm enhances the design materials particularly if they show reflection and transparence (figure 2), and allows us to point out shapes articulated in space, by means of the complex simulation of light paths. The exact definition of light and dark effects is particularly valuable for the representation of conditions of direct illumination, as in the case of exteriors.

In the case of less direct illumination, or illumination from several light sources, which may interact, the radiosity algorithms produce more blurred results, in which we can appreciate the coexistence of parts in light and in shade and the cumulative effect of different light sources (figure 3). The edges of the objects are often indistinct, also because the transition between light and dark is not sharp. The radiosity algorithms are particularly suited to the representation of interiors, or at least scenes in which the illumination is blurred, indirect or coming from many sources. The distinction between ray tracing and radiosity algorithms will remain effective at least until a synthesis between their properties is achieved (Wallace et al. 1989).

Simulation of Light Sources

Simulation programs allow us to carry out experiments to examine the result of a given illumination in a specific context or environment. In particular ray tracing algorithms allow us to define exactly the nature and characteristics of each illuminating source. There are three main characteristics which permit a physical *definition of a light source: geometry, emitted spectral distribution and luminous intensity distribution. With these three characteristics the nature of any light can be approximated, whether natural or artificial. We can define exactly the position and characteristics of each light, including the characteristics of reflectors and shields, if any. We can render with great precision the characteristics of a specific environment.*

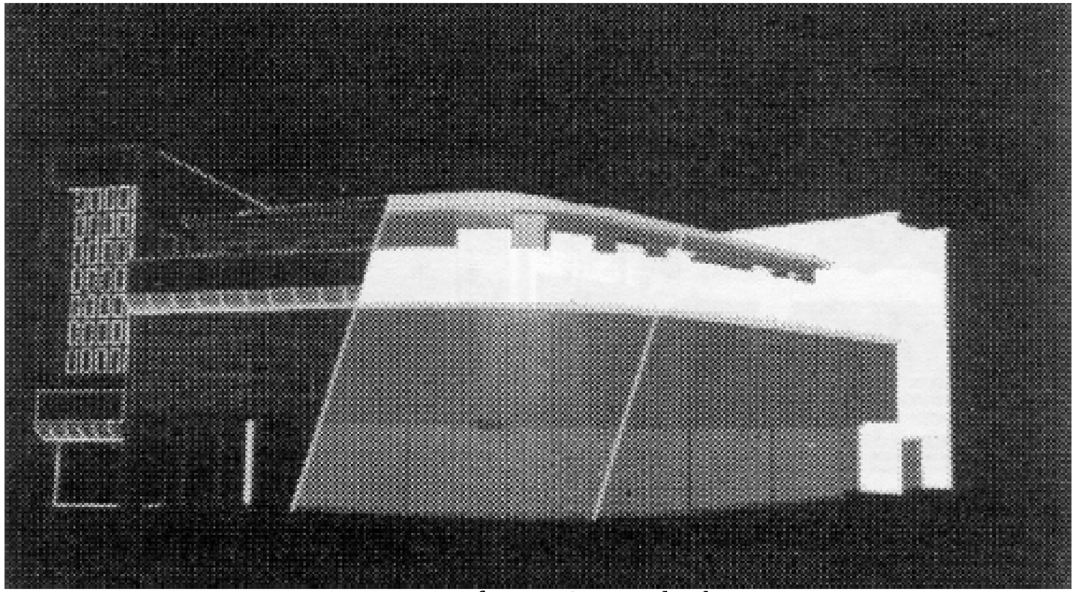


Fig. 1 - Wire-frame, Gourand, Phong.

The result of the simulation is not values or charts, but rather the photo-realistic simulation of that environment. The computer-generated image of a theater, an art gallery (figure 4), or of any other space in which there is complex interaction of light- shape-color, is able to describe the result of sophisticated simulation models more effectively and more clearly than analytical methods. Without affirming that one method is superior to all others, it is true, however, that graphic representation of information is able to reveal spatial relationships and configurations which could hardly be recovered from numerical data alone.

Materials

Architectural design consists of many elements, one of which is the physical nature of building materials. With C.G. it becomes possible to render this "materialness", even before the design is put into effect. Here we are faced with the concept of representation, much discussed in various contexts, from physics to painting and architecture, and yet we find ourselves facing it by means of new technological tools. C.G., on the one hand, integrates digital image elaboration, above all photographic, and on the other, mathematical descriptions of materials, mainly based on fractal geometries.

Photographic Textures and Bumps

In C.G. textures are a "venerable" procedure which refers to the possibility of acquiring an image, perhaps from photography or another source, and hence of applying a mathematical deformation, in order to map it on to the geometry of an object (Catmull 1975).
The object, "mapped" in this way, can be visualized with the algorithms described above. The photographic image is rendered deformed according to the geometry of the object to which it is applied, and according to the perspective projection relative to the point of view, while the illumination of the scene determines which

parts of the material are in light or in shade, according to the mutual positions of object, observer and light.
Tiles, wood, marble, concrete and other materials which compose and characterize the design may be rendered by means of photographic textures. In restoration, textures can be used to visualize the images of existing frescoes and mosaics.

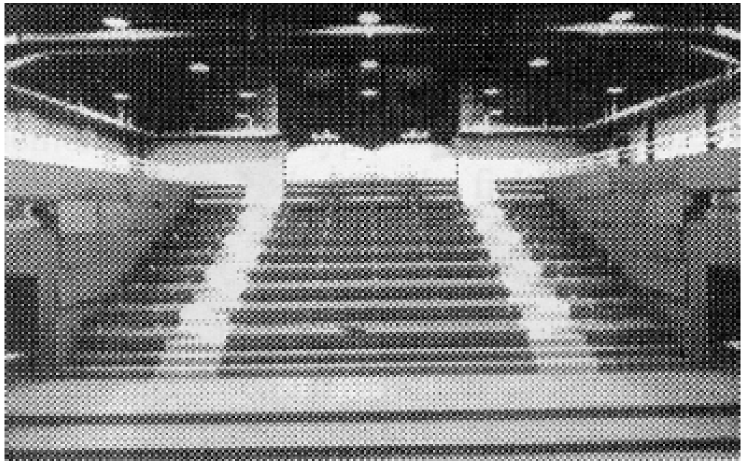


Fig. 2 - Ray tracing

Fig. 3 - Radiosity

There is a further use of photographic textures which not only affects the surface, covering it with a photograph, but creates the illusion of an alteration of the surface on which it is applied. These are humps, which at a given point modify the angle of the normal to the surface, in order to create a sensation of a surface roughness, unevenness, bas-relief etc.
For example, the photograph of a brick wall can be used in order to achieve a similar result in a new design. In order to arrive at an effect of materiality in the simulation of the wall, in most cases, the application of a photographic texture seems unsatisfactory, as it is free of that irregularity, those little roughnesses, which cause the light to be unevenly reflected from the wall. In short, it looks more like a poster of a wall than a real wall. The integration of the texture with the bump allows us to avoid this problem: light is no longer uniformly reflected from the wall, according to a single normal, but along local trajectories, which differ from point to point.
For the designer, the use of textures is an operative tool for rendering the detail of a design, including photographs of the materials to be used.
The limitations of textures and bumps arise from the limited deformability of a photographic image, from the visualization of an equal amount of information near and far from the observer, and from the practical difficulty of acquiring images of the design materials which are suitable in terms of definition, scale, color etc.

Procedural Textures

In some materials, natural and artificial, the surface appearance indicates a structure, or an internal organization, which the designer may want to show. For example, in a block of wood, the direction of the grain on the various facets allows us to recognize the direction in which the cut has been made. This visual effect is extremely difficult, if not impossible, to render by means of photographic textures, which deal only with the surface of the object and not with the volume in relation to the structure of the specific material.
Recent developments in mathematics may indicate that forms exist in nature which geometry can in some way represent. Beinot Mandelbrot affirms the existence

of a geometry of nature, actually entitling one of his books "The Fractal Geometry of Nature" (1982).

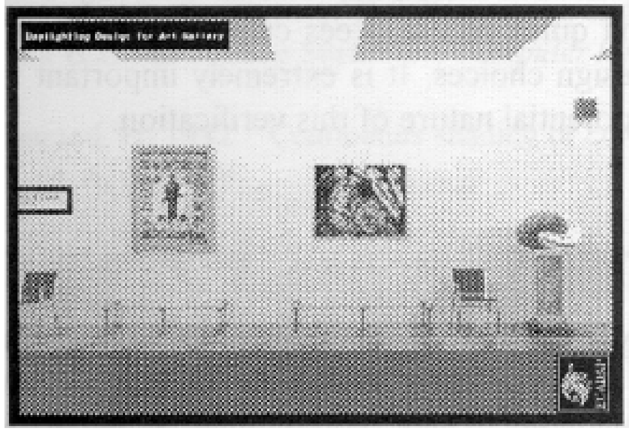


Fig. 4a - Art gallery illuminated by skylights.

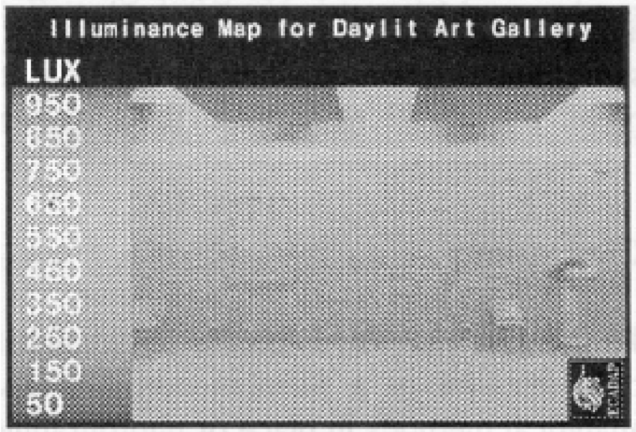


Fig. 4b - Corresponding surface illuminances.

For the last twenty years or so, C.G. research has been concerned with the visualization of the mathematical models underlying numerous natural and artificial forms (incidentally, many of these models could not have been studied without the visualizations of C.G.). The first results of this research prompt a new approach to the visualization of materials, some of which could previously be rendered by means of photographic textures. Today, the designer has at his disposal procedural descriptions of marble, wood, stucco, stone, plaster, brick (figure 2), and the list is still growing. Procedural textures allow a new approach to rendering, first and foremost applying to objects of all kinds of complexity and spatial articulation. Moreover, fractal geometries can be enlarged or reduced to any scale of representation, without loss of detail: on the contrary, greater enlargements permit the discovery of new structures and forms within the regularities of the simulated material. But above all, they open up a new creative dimension for the designer, as they leave under his control parameters such as color, density, grain or vein ..., of the materials, allowing her/him to try new design solutions within the limits of the building constraints and beyond, to the dimension of pure creativity.

Hyper-textures

The transition from a representation confined to the surface to a procedural description of the global volume of the object has been the means of realization of a new family of textures, the hyper-textures (Perlin et al. 1989), which modify the geometry of the object, introducing perturbations and regularities with a view to rendering phenomena which cannot be modeled by the discretization process used previously. Water, fire, clouds, waves, textiles, sand are some of the phenomena and objects which can be rendered. Although not all of them can be of direct interest to the designer, we must bear in mind that they are the result of recent research, which, rather than providing operative tools, shows the direction of evolution. Moreover, we must not forget that architectural rendering is a relevant domain in C.G. research, but research is rarely dedicated to it. Innovations for the most part originating outside research on architectural rendering are applied to it.

Hyper-textures offer the designer a notable gain in terms of control of representation, freeing the rendering of materials both from operative constraints, imposed by the need to acquire a photograph of each of the materials, and from creative constraints, affecting the possibility of visualizing designs of any level of complexity. The availability of an almost unlimited library of materials, easy and quick to use, frees creativity, and at the same time offers a constant verification *of design choices. It is extremely important for possible applications to define the actual and potential nature of this verification.*

Conclusions

To increase the visual -perhaps one might say "realistic" or even illusionistic- properties of a material or a phenomenon, we have recourse to a stratagem: simulation with analytical methods in place of photographic rendering. This is nothing new in the history of art: for hundreds of years painting has sought the achievement of the true by means of the introduction of theories and techniques. "The painter (...) before taking up his pencil or his brush, must tune his eye to a form of reasoning according to the principles of art, which teaches how to see things not only as they are in themselves, but also as they should be represented" (Fréart de Chambray 1662).

Thus the novelty lies not in the introduction of a further technique but in the peculiarity of the tools: the simulation of phenomena and objects, by means of the conceptual tools proposed by modern mathematics and geometry, is a bridge between the concept of representation proper to art, and that of simulation, proper to physics. At certain moments the relationship set up between science and art is biunivocal, or rather it is no longer art alone that mediates new theories from science, but science that seeks confirmation of its theories in the visual -graphic- computer-simulated representation.

For the designer who mediates physical reality with psychological space, the "new covenant" -as in the expressive title of the book by Ilya Prigogine and Isabelle Stengers (1979)- between science and art, makes available new cognitive tools, based on rigorous physical models. The traditional concept of architectural representation is enriched by the concept of simulation, through the methods of physics. Computer Graphic renderings can be for the designer additional communicative, cognitive and interpretative tools.

Acknowledgments

Figure 1 was created by Marilena Gai of Archimedia Inc., this image was the first prizewinner in the "CAD/Still image" category at the Truevision Contest, Siggraph '92, figure 3 was created by Dan Baum et al. of Silicon Graphics Inc., figures 4a and 4b were created by John Mardaljevic of the ECADAP Group at the De Monfort University.

References

Bruschi, A. 1969. Bramante architetto. Bari: Laterza, 459.

Catmull, E. 1975. -Computer display of curved surfaces". Proceedings, IEEE Conference on Computer Graphics Pattern Recognition and Data Structures, 11-17.

Fréart de Chambray, R. 1662. Idée de la perfection de la peinture. Mans: Ysambart.

Goral, C.M., K. Torrace, D.P. Greenberg and B. Battaile. 1984. "Modeling the Interaction of Light Between Diffuse Surfaces". Computer Graphics. 18, no. 3, 213-222.

Gourand, H. 1982. "Continuous shading of curved surfaces". IEEE Transactions on Computers, 20, no. 6, 623-629.

Mandelbrot, B. 1982. The Fractal Geometry of Nature. San Francisco: Freeman.

Manetti, A. 1976. Vita di Filippo Brunelleschi. Milano: Ed. il Polifilo.

Newton, I. 1728. Optical Lectures. London: Innys.

Perlin, K. and E.M. Hoffert. 1989. "Hypertextures". Computer Graphics, 23, no. 3, 253-262.

Phong, B.T. 1975. "Illumination for Computer Graphics". Communications of the ACM, 18, no. 6, 449- 455.

Prigogine, I. and I. Stengers. 1979. La nouvelle alliance. Métamorphose de la science. Paris: Gallimard.

Wallace, J., K. Elmquist and E. Haines. 1989. "A Ray-Tracing Algorithm for Progressive Radiosity". Computer Graphics, 23, no. 3, 315-324.

Whitted, T. 1980. "An Improved illumination Model for Shaded Display". Communications of the ACM, 23, no. 6, 343-349.